1 Evolution of embedded intelligence

We are surrounded by products that have minds of their own. Computing power, in the form of microcontrollers, microprocessors, sensors, and data storage chips, has become so cheap that manufacturers are building microcomputers and embedded software programs into all types of consumer goods. According to market research firm Databeans, microcontroller shipments worldwide will reach fourteen billion units by the end of 2010 (Databeans, 2009). Along with these chips have come a host of advanced product features and the penetration of embedded product intelligence into daily life.

Everyday appliances can now keep track of how often we use them and remind us when it is time to order new batteries or replacement parts. Alarm clocks get louder and louder, or flash a light if we ignore their morning summons. Coffee pots turn themselves on, grind the beans, and brew our first cup at just the strength we prefer. Mobile phones can download our email, display digital photos, remind us of today's appointments, and let us scan the Internet for breaking news over breakfast. Or we can start the day by listening to music on our iPod, watching the morning news reports on our high-definition television (TV), and setting up the recording of a new television series on the digital video recorder (DVR). If we forget about them in our rush to get to work, our steam irons, coffee pots, and toaster ovens will sound an alert, or simply switch themselves off to save power and avoid overheating.

Heat and air conditioning don't even need our daily attention – if we have a smart thermostat, it automatically adjusts temperature settings to match our morning departure and evening return. When we hit the road, dozens of sophisticated computer chips in our car manage the interactions among the engine, braking, steering, and

other systems, record any performance problems that will need special attention at our next dealer service appointment, calculate the shortest route to our destination, and read the turn-by-turn directions aloud to keep us on track. Such encounters with embedded intelligence are barely noticeable in the first hour of a day that will be filled with similar man–machine interactions.

In fact, smarter consumer products have been proliferating for years in parallel with the increased capacity of computer chips and more recently the spread of Internet and wireless connectivity. In the past ten years low-cost microchips and ubiquitous network access have combined to bring advanced computing and communications capabilities to a long list of consumer goods. The integration of machine intelligence into our daily lives and the capabilities of today's appliances, mobile phones, automobiles, and other consumer possessions seem to have evolved quite naturally. After decades of visionary predictions about personal robot assistants, self-driving autos and home electronics that adjust themselves to our varying moods, it is hard to pinpoint any single smart product development that has burst on to the scene faster and more dramatically than anyone expected.

As long ago as the 1970s, computer enthusiasts were optimistically discussing the imminent arrival of widespread embedded intelligence and painting a generally rosy picture of its impact on consumers. One of the many books that celebrated the computer's power to transform society for the better was *The Micro Millennium* by Christopher Evans. Evans boldly predicted that by the year 2000, the integration of microcomputers into all types of products would revolutionize every aspect of our lives: "You will live in a world transformed by one tiny, cheap computer chip – the microprocessor! The microprocessor – the computer chip that processes huge amounts of information in a fraction of a second!"

Among the breakthroughs that Evans foresaw as a result of microprocessor adoption were "A pocket-size diagnostic aid for doctors, containing all relevant information; Ultra-informed machines

programmed to solve world problems; Dolls and mechanical toys that respond to a spoken word; and Robots ready to cut the lawn" (Evans, 1979).

Just as today's product realities seem poised to catch up with the predictions of 1979, some planners are envisioning a future world of ultra-intelligent machines that will decisively overtake the capacity of the human brain and lead to self-directed computer power:

> Intelligent nanorobots will be deeply integrated in our bodies, our brains, and our environment, overcoming pollution and poverty, providing vastly extended longevity, full-immersion virtual reality incorporating all of the senses (like "The Matrix"), "experience beaming" (like "Being John Malkovich"), and vastly enhanced human intelligence … We'll get to a point where technical progress will be so fast that unenhanced human intelligence will be unable to follow it. That will mark the Singularity … I set the date for the Singularity – representing a profound and disruptive transformation in human capability – as 2045.
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> *(Kurzweil, 2005)*

In contrast to living inside The Matrix and overcoming world poverty, watching TV on a smartphone or operating a robot lawnmower are bound to seem mundane. Just because today's smart products have evolved over decades, however, doesn't mean that they are less capable of upending business strategies and transforming consumer behavior. The impact of ubiquitous product intelligence is worth a closer look. It's likely that those familiar household products are already a lot smarter than you think and it's certain that they will be getting even smarter in the next five years.

Most of the fourteen billion microcontrollers shipped in 2010 are not yet connected to other devices. However, the options for adding low-cost, wireless connectivity to smart products are increasing year by year. A significant percentage of microcontroller chips already have wireless or fixed network connections and analysts

predict that the number of intelligent, Internet-connected devices will reach fifteen billion by 2015 (Gantz, 2009).

Extending the power of Internet connectivity to a virtually limitless variety of embedded devices, many of them able to communicate machine-to-machine without human intervention, has far-reaching business and personal implications. Consumer products like the iPhone and the Kindle are already reshaping entire industry sectors and creating new multi-billion dollar content and service markets just as the emergence of personal computers (PCs) did in the 1980s. The hard-pressed automotive industry is counting on smarter connected vehicles to revive demand and improve profit margins. The rapid growth of global investment in smart grid and smart meter technologies is opening up power generation and distribution to new and potentially disruptive alternative energy models.

Smart products have certainly captured the attention of technology leaders and global corporations. Predictions of ever more dramatic industry and market transformation based on the next generation of intelligent, interconnected devices abound. Doug Davis, the Vice President of the Digital Enterprise Group at Intel Corporation, puts it this way:

> Generations of new intelligent devices will carry your ideas further into the embedded world than has ever been possible before, in the form of self-configuring networks of wireless "motes," smart factory robots, personalized in-vehicle infotainment systems, mobile medical diagnostic tools, and intelligent shopping carts. Billions of these devices will do for the embedded world what the Internet has accomplished for human beings – transcend boundaries, invent new functions, and redefine the way we live and work. As an industry, we face the amazing challenge of creating an era of embedded communications that will enable embedded devices to stay in constant contact with each other … Extending the goodness of the Internet to the embedded space will have far-reaching

> implications that we have only begun to imagine. Making it happen will be the ride of a lifetime.
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> *(Davis, 2009)*

IBM has launched a major marketing campaign to associate itself with all types of connected, embedded solutions for a smarter planet. Its white paper "Smarter Products: The Building Blocks for a Smarter Planet," presents the vision of a transformational new era of creativity and productivity based on "smarter products [that] can better adapt to the unique needs, preferences, and characteristics of consumers to get things done."

In describing how this transformation will come about, the white paper continues:

> How is this all happening? What is new? Product companies are tapping into accelerating innovation using embedded software control – the new "brains" that make products smarter. When software is effectively fused with micro-electronic, actuator, sensor, and mechanical technologies, products can become increasingly intelligent, instrumented and interconnected. That is, they can respond to changes quickly and accurately and produce better results by anticipating and optimizing for future events. They can measure and sense the relevant condition and are able to interact with other products, people, and IT systems in entirely new ways. This is what makes them "smart" – their ability to adapt to the unique needs of individual businesses and people.
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> *(Hebner, 2009: 2)*

Much of the discussion of smart products by industry advocates assumes that new product features such as "anticipating and optimizing for future events" after the product measures and scans the relevant conditions will be welcomed and valued by consumers. Further, many companies have built business and service plans that assume smart products will command premium prices and build

recurring revenue streams, creating competitive advantage. Apple's success in tightly linking the iPod device with an iTunes store, followed by a worldwide consumer embrace of the iPhone and its App store have demonstrated the financial rewards and brand loyalty advantages of controlling the content and application markets for a company's branded smart products. This success has helped to fuel a raft of competitors and imitators of the Apple smart product and content strategy. It also reinforces the perception that consumers will have a keen appetite for smart products in other market sectors.

However, the smart product value proposition for consumers is complex. In some cases industry evangelism for embedded intelligence is not grounded in an understanding of the many challenges presented by smart products and their evolving ecosystems. There are numerous examples of smart products that never captured the consumer market or that fell out of favor when lower-cost, more generic offerings came along. Consumers also have concerns about the potential negative impact of bringing more connected, intelligent products into their lives. If such products are designed "to interact with other products, people, and IT systems in entirely new ways," who will be in charge of the information that they transmit, or the decisions that they make?

Many consumers and privacy advocates are already troubled by the prospect of being surrounded by hundreds of devices that are sensing, measuring, and possibly reporting on exactly what individuals do and don't do throughout the day. What happens if the product's embedded intelligence is programmed to adhere to a built-in set of rules that its owner didn't set and doesn't want to follow? Perhaps the coffee maker is designed to use only its own capsules, meaning that it won't work with a competitor's brand of beans. Maybe the digital music that you paid to download to your iPod won't play on your new computer, or perhaps the media player embedded in your PC or your smartphone limits the number of

times that certain music or video content can be played. Suppose the toaster oven you forgot to turn off sends a message to your doctor or your insurance company that this is the third instance of such absent-mindedness within a week? What if your smartphone is reporting all of your music and application downloads and Internet browsing habits to a third party that sells your preference profile to the highest bidder?

Perhaps your laser printer has automatically ordered new full-price ink cartridges even though you just stocked up at the office supply store sale last weekend. Or maybe when you stop at a garage because the "check engine" light is flashing ominously on your dashboard, the mechanic can't help you because the software to access the engine diagnostic system is only available through the auto dealership. To top it all off, you get home after a long, hot day at work and find that the smart thermostat has turned off your air conditioner in response to a signal from the utility company to conserve power. Instead of welcoming their assistance, you find yourself looking at all your intelligent possessions and wondering, "Who is in charge here?"

Not all of the projected fifteen billion Internet-connected devices produced in 2015 will be consumer products, of course. Smarter products and services are not just focused on consumer markets; robust growth for wireless sensor networks, radio frequency identification (RFID) chips, and other forms of machine-to-machine implementations will account for a large percentage of the so-called Internet of Things. As of 2010 there are approximately seven billion people in the world, but it's estimated that there are more than fifty billion machines in existence that could be connected to the Internet and to the billions of new microcontrollers shipped every year.

Before we can analyze the business and social impact of smart products, we need a more precise definition of exactly what products we have in mind and a better understanding of their technology

origins and evolution. Defining the core characteristics of smart products designed for today's consumer market will be the focus of the next section.

DEFINING SMART PRODUCTS

Even in the realm of consumer products, the feature of connected embedded intelligence and the term "smart product" are used to describe a myriad of objects as disparate as automobiles, mobile phones, and electric utility meters. When applied to home appliances such as refrigerators and dishwashers a decade ago, the smart descriptor typically meant that the appliance was connected to the Internet. Now it is more likely to indicate an interface with a smart utility meter that sends the appliance signals about the cost of electric power at different times of the day and monitors its energy consumption.

The smart designation has been applied to so many products so frequently, and in so many different contexts, that it is becoming more of a marketing claim than a well-defined technical description. Which consumer devices should be categorized as smart products? While the rapid growth in embedded computing power and the absolute number of microcontroller chips are well-documented facts, the definition of a smart product is still evolving. Definitions differ considerably depending on the point of view of the writer. We will review some definitions that have particular applicability for products that target the consumer market and then provide a description of the specific product characteristics and capabilities that are most relevant for our analysis.

According to Stanford University's Smart Product Design Laboratory, the presence of an embedded microprocessor is the defining technical characteristic of a smart product: "Smart Products are products whose functionality is increased by an embedded microprocessor. It is a superset of the field that has become known as Mechatronics. Embedded microprocessors can already be found

in everything from dishwashers to automobiles – and more Smart Products appear every day" (Stanford, 2009).

This is an appealingly simple definition. It encompasses the billions of microcontroller units (MCUs) that are sold into the marketplace every year and highlights specific consumer product examples. However, many MCUs are aimed at product engineers, enterprise product manufacturers, and enterprise machine-to-machine services rather than at the consumer products that are our focus. This makes the Stanford perspective too broad to pinpoint the essential characteristics of consumer smart products.

A search for narrower definitions in the field of mechatronics quickly takes us down an even more technical path. According to the editor of *Mechatronics: The Science of Intelligent Machines*, a journal of the International Federation of Automatic Control, "Mechatronics is the synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes" (Steinbuch, 2009).

With articles like "Efficient class-B analog amplifier for a piezoelectric actuator drive," and "Application of the continuous no-reset switching iterative learning control on a novel optical scanning system," it is clear that the engineering context of the mechatronics journal is a world apart from describing smart products as they operate in the consumer marketplace.

A 2007 study on the impact that enhanced product intelligence has on consumer satisfaction provides a more accessible definition that blends embedded technology features such as sensors and software with the ability of smart products to collect and produce information of value to consumers. This article defines smart products as follows: "Intelligent products are products that contain IT in the form of, for example, microchips, software and sensors, and that are therefore able to collect, process, and produce information" (Rijsdijk *et al.*, 2007).

Researchers in the SmartProducts research project funded by the European Union provide an even more detailed definition that emphasizes the self-aware and interactive aspects of embedded product intelligence:

> "Smart Products" are real-world objects, devices or software services bundled with knowledge about themselves and their capabilities. These properties make Smart Products not only intelligible to users, but also smart to interpret user's [sic.] actions and adopt accordingly. By naming these objects Smart Products, we convey not only the notion of technology available "off-the-shelves", but also the notion of componentized software services and hardware objects required to assemble new, innovative end-user components. Therefore, Smart Products share some key properties: the ability to have multiple uses, be deployed independently, and network with others to augment their individual and collective capabilities.
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> *(Lyardet and Aitenbichler, 2008)*

This definition encompasses the consumer product subset of those billions of objects with embedded microcontrollers that would qualify as smart products according to the Stanford Design Lab approach. It has the advantage of highlighting characteristics that make product intelligence visible and broaden its sphere of impact through networking with others; factors that have become particularly important to product designers and manufacturers in the era of widespread Internet and wireless connectivity in homes and offices.

However, this and the other definitions do not include the concept of preprogrammed control of the device, including limits on how the device can be used by its owner after purchase. As we will discuss in more depth in the following chapters, embedded controls can be fixed at the point of manufacture or can be updated and enforced through the product's network connections. The use of such controls to accomplish business objectives independent of the wishes of the product owner is an important issue. Our analysis will